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DEVELOPMENT OF BIOGAS-POWERED MICROTURBINES WITH ULTRA-LOW EMISSIONS

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

Biogas, commonly found at industrial and agricultural sites, is a mixture of gasses produced by various feedstocks, including organic wastes, animal manure, and wastewater treatment. Biogas generally contains between 40 to 70 percent methane and significant quantities of inert gases. Since inert gases dilute the reactivity of methane, a specific fuel handling system and a combustor capable of handling biogas is necessary. The goal of this project was to develop and demonstrate a new microturbine combustion system which meets the California Air Resources Board 2013 ultra-low emissions targets. The concept for the combustion system was based on the low-swirl combustor technology developed at Lawrence Berkeley National Laboratory. The approach was to engineer a low-swirl combustor, specifically for biogas operation, integrated with an existing microturbine. This project had two major phases: (1) lab testing under simulated gas turbine conditions, and (2) incorporation and testing of a microturbine. The low-swirl combustor was tested in a laboratory under simulated gas turbine conditions and demonstrated the ability to operate with fuel blends of up to 60 percent carbon dioxide. Under these conditions, the combustor achieved nitrogen oxide emissions levels equivalent to the California Air Resources Board 2013 requirements; carbon monoxide emissions were still higher than acceptable limits. When incorporated in a Capstone C60 microturbine, flame stability concerns limited the low-swirl combustor to operate at higher firing temperatures, resulting in higher nitrogen oxide emissions than acceptable by California Air Resource Board targets. Overall, the results illustrate that the low-swirl combustor concept can power microturbines with biogas, but needs further development to meet the 2013 California Air Resources Board emissions targets in a Capstone C60. By offsetting purchased natural gas with biogas, California taxpayers can save $280 million per year based upon average 2012 California industrial natural gas price.

Keywords: Biogas, low-swirl combustor, microturbine, distributed generation, renewable fuels

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EXECUTIVE SUMMARY

Introduction

Biogas is a mixture of gasses produced by the breakdown of organic wastes such as animal manure and wastewater treatment. Disposal of these waste streams generates environmental hazard and financial costs. Therefore, using biogas to produce energy not only diverts waste streams from landfills and other off-site disposal, but also reduces the consumption of fossil fuels. By replacing purchased natural gas with biogas, California ratepayers can potentially save $280 million per year based upon the average 2012 California industrial natural gas price. Before this plan can be implemented, innovations must be made to current technologies able to use biogas. Biogas generally contains 40 to 70 percent methane with significant quantities of inert gases, such as carbon dioxide and nitrogen. However, these inert gases dilute the reactivity of methane in such a way that burning a cubic foot of biogas may yield less than half of the heat produced from burning a cubic foot of natural gas. To cope with the decreased energy content and reactivity of biogas, the fuel handling system and combustor assembly must be designed specifically for biogas.

Project Purpose

For onsite power generation, microturbines offer unique attributes that enable them to be more effective at generating power from biogas. Thus, the goal of this project was to develop and demonstrate a new microturbine combustion system able to meet California Air Resources Board (CARB) 2013 ultra-low emissions targets. The concept of the combustion system was based on the low-swirl combustor (LSC) technology conceived and developed at Lawrence Berkeley National Laboratory (LBNL). While there are many combustion technologies that can achieve low emissions levels (such as catalytic combustion or combustion with selective catalytic reduction system) the combination of low cost, wide operating range, high reliability, and fuel flexibility make the LSC particularly suitable for this application.

Project Results

This project consisted of two major phases: (1) laboratory testing of a "stand-alone" low-swirl combustor at atmospheric and simulated gas turbine conditions, and (2) incorporation of the low-swirl combustor to a Capstone C60 Microturbine and operation under a typical run cycle.

The product of phase 1 is a fully-functioning, silo-shaped low-swirl combustor with laboratory tests results obtained at atmospheric conditions and at simulated gas turbine conditions. Laboratory tests offer a well-controlled environment to establish the potential of the low-swirl combustor in meeting performance targets. The tests were designed to investigate the operational characteristics of the low-swirl combustor when fueled with biogas and to evaluate its readiness for incorporation into the Capstone C60 Microturbine. The design of the low-swirl combustor is generic. It consists of a multi-spoke fuel injection system feeding into a single burner which fires into a cylindrical combustor. The insights and knowledge gained from phase 1 can be transferred to adapting the low-swirl combustor technology to the Capstone C60 as well as to other microturbine systems.

Laboratory tests of the low-swirl combustor at atmospheric pressure using natural gas and simulated biogas confirmed basic operation characteristic such as ignition, flame stability, combustor interactions, and emissions. Regardless of fuel, the nitrogen oxide (NO_x) emissions were just above 10 parts per million (ppm), corrected to 15 percent oxygen (O_2) at a flame temperature approaching 3000°F (1650°C). These NO_x emissions are consistent with those from atmospheric tests of LSC injectors developed for larger gas turbines. The carbon monoxide (CO) emissions trend is also typical of LSC injectors with the highest at the lowest flame temperatures due to the exhaust not being sufficiently hot enough to completely burn out CO. Subsequent laboratory tests at simulated microturbine conditions, like elevated temperatures and pressures, generated similar results. As expected, NO_x emissions were found to increase with flame temperature, with most measurements below 10 ppm at 15 percent O_2. These tests confirmed that the technology is capable of meeting the CARB 2013 emissions target for NO_x. Emissions of CO however were on the order of 10 ppm at 15 percent O2, and considerably higher with flame temperatures below 3272°F (527°C), implying that an oxidation catalyst may be required to meet CO emissions targets. The results are the benchmarks for evaluating the performance of the Capstone C60 Microturbine when fitted with the low-swirl combustor.

The compact and integrated nature of the Capstone C60 Microturbine necessitated the Silo-LSC to be mounted externally to the engine frame. A network of insulated pipes and manifolds was constructed to reroute the flow path of the C60 to deliver the compressed high temperature air to the silo LSC and returning the hot combustion products back to the turbine. The test results were mixed because of this piping network. While every engineering design effort was employed to reduce the pressure losses in the piping network, the pipes created pressure drops (flow friction) that were much higher than the acceptable design limit of the C60. Consequently, the Silo LSC powered C60 was not capable of generating net electricity power output. Nevertheless, a series of tests were performed on the modified engine using simulated biogas. The emissions results were similar to those obtained in the laboratory at simulated gas turbine conditions with NO_x emissions highly correlated with firing temperature. To maintain stable operation of the engine it was necessary to operate the combustor at a higher firing temperature than the design point of 1790°F (1250°K) to avoid blow off. The limited number of data points at emissions data at 1790°F (1250°K) show NO_x emissions on the order of 20 ppm while CO emissions were below 10 ppm corrected to 15 percent oxygen.

Project Recommendations

While the present work has demonstrated that the LSC is capable of powering a microturbine with biogas, the current system is not optimized due to the use of a network of pipes and manifolds to connect the LSC to the Capstone C60 Microturbine. The connecting piping network created additional pressure drop (flow friction) in the flowpath, which impeded the capability of the modified C60 microturbine to produce net electricity power. Therefore, additional work is needed to reduce these pressure drops before the system can be deployed for demonstrations at the Chiquita Water Reclamation Plant.

While the emissions data from the laboratory demonstrated that the technology was capable of meeting CARB emissions targets, ultra-low emissions have yet to be achieved in the C60. This was due to the larger than expected fluctuations of CO_2 concentration in the fuel which restricted the LSC to operate at a higher firing temperature to maintain stability. The researchers do not anticipate this to occur if the system were deployed to a wastewater treatment plant because the fuel composition would be considerably less variable, allowing for operation at desired lower combustor exit temperature needed for reducing NO_x emissions. Additionally, the laboratory tests have shown that CO emissions may be a concern if temperatures are reduced. Under these conditions, it is likely that an oxidation catalyst would be needed.

Project Benefits

This project benefits the State of California by contributing to the renewable energy portfolio via an enabling technology to exploit the potential of turning waste streams into clean energy. The low-swirl combustor technology is simple and has the potential of deployment in biogas powered electricity generators to attain high efficiency and meet ultra-low emissions. Broader utilization of biogas in California offsets purchased natural gas. Fully utilization of biogas potentials in California can save taxpayers $280 million per year based upon average 2012 California industrial natural gas price.

CHAPTER 1: Introduction

1.1 Background and overview

1.1.1 Motivation

Biogas is derived from a number of feedstock commonly found at industrial and agricultural sites. Sources include organic wastes, animal manure, and wastewater treatment plants. The National Renewable Energy Laboratory estimates the potential to produce 1,100 thousand tonnes (500 million Therms) of methane in the form of biogas from these sources in California each year (Nat'l Renewable Energy Laboratory, "Energy Analysis"). Full utilization of this biogas potential would offset 14.3% of statewide industrial and agriculture natural gas consumption and 2.14% of total statewide natural gas consumption. By offsetting purchased natural gas with biogas, California ratepayers will save $280 million per year based upon average 2012 California industrial natural gas price. If biogas were used to offset natural gas consumption at more locations, cost savings would be even greater due to higher natural gas tariffs.

Biogas is produced from the digestion of organic waste, animal manure, and wastewater, waste streams from industrial and agricultural sites. Current disposal of these waste streams generates environmental and financial costs. Therefore, the use of biogas to produce useful energy not only results in waste stream diversion from landfills and other off-site disposal, but also reduces the consumption of fossil fuels. In California, biogas is currently used predominantly for on-site power generation. With additional clean up, the biogas can also be upgraded to pipeline quality (biomethane) for injection into the natural gas pipelines distribution system. However, on-site utilization of biogas at large facilities such as wastewater treatment plants, landfills, and large dairies where organic waste is consistently available to maintain a constant supply, which is far more cost-effective and efficient than conversion to biomethane.

Biogas generally contains methane of 40 to 70% methane with significant quantities of inert gases, such as carbon dioxide and nitrogen. These inert gases dilute the reactivity of methane such that burning a cubic foot of biogas may yield less than half of the heat produced from burning a cubic foot of natural gas. Additionally, these diluents reduce the flame speed and heat release density of the fuel, so that combustion occurs more slowly and in a larger volume. These factors can lead to difficulties in achieving proper combustion of the fuel when biogas is fed to a combustion system such as a gas turbine that is designed for operation with natural gas. Since biogas has lower specific heat content than natural gas, a higher flow rate of biogas is needed to obtain the combustor's rated heat output compared to natural gas. The fuel handling system in gas turbines designed for natural gas operation may not be capable of supplying the necessary flow of biogas fuel. Therefore, the combustor assembly must be designed for optimum performance with biogas.

For onsite power generation using biogas, microturbines offer unique attributes that enable them to compete against reciprocating engines ("Cogeneration and Onsite Power Production").

There are several manufacturers in the United States that offer microturbine products for biogas operation. For example, since the early 2000's, Capstone Corporation of Chatsworth California had installed over 30 units with output power ranging from 30 kilowatt (kW) to 200 kW at water treatment plants in California and other states. Due to the lower heat content, a biogas-powered microturbine needs a larger flow rate of fuel gas than an equivalent natural gas-powered microturbine. Consequently, the compressor, controls, and other fuel handling components must be re-sized for optimum operation. The combustor assembly may need a larger volume to accommodate the slower flame speed and to improve burnout of carbon monoxide and unburned hydrocarbons. The air flow split between primary (combustion) air and secondary air may require adjustment to increase the exhaust temperature to the desired level for the turbine inlet.

With the implementation of the California Air Resources Board (CARB) 2013 targets for NO_x and CO emissions from non-natural gas fuels such as those from waste and other bio derived sources, new combustion technologies are needed to meet these stringent air quality rules. The goal of this project is to develop and demonstrate a new microturbine combustion system that meets CARB 2013 ultra-low emissions targets. The combustion system is based on the low-swirl combustor (LSC) technology conceived and developed at Lawrence Berkeley National Laboratory.

Although the low swirl combustor is among many other lean premixed combustors and catalytic combustors under consideration for microturbines (see table 1 below), it has many attributes in terms of cost and performance that make it particularly suitable.

Table 1: Comparison of Low-Swirl Combustor Technology and Other Developmental Microturbine Technology

	Initial Cost	Operating & Maintenance Costs	Operating Stability	Reliability & Durability
Low Swirl Combustor	Low	low	Excellent	high
Other Lean Premixed	Moderate	varies	Fair	moderate
Catalytic Combustor	High	high	Limited	low
Std Combustor + SCR	High	high	limited by SCR	low

For example, the cost of selective catalytic reduction (SCR) - a tailpipe treatment for NO_x control can be quite high (more than $500 per kW) in microturbines, making it economically unfeasible for almost all installations. SCR also has significant operation and maintenance requirements due to the catalysts limited operational lifetime. Catalytic combustors have the capability of operating on biogas with acceptable levels of pollutant production. However, the catalysts also have limited operational life, degrade with use, and are susceptible to poisoning by sulfur, which is commonly found in biogas. The only economically viable solution to achieve ultra-low NO_x emissions from a biogas-powered microturbine is a robust lean premixed combustor system such as the low swirl combustor.

1.1.2 Air Quality Driver

California is a leader in the development of clean sources of power. In 2007, CARB has implemented new standards for distributed generation systems powered by fossil fuels that require significantly lower allowable emissions of NO_x, CO, and volatile organic compounds (VOCs) from generators. These standards make allowances for system efficiency, like those expressed in terms of pounds per mega-watt hour (lb/MWhr). CARB recognizes that it is difficult for microturbines to operate cleanly on waste gas such as biogas. From public hearings on emission standards for distributed generation systems, it was determined that systems operating on waste gas such as biogas will be regulated separately from fossil fuel-powered systems. In a proposed rule on distributed generation that as finalized in summer of 2007, systems operating on waste gas will be given an additional five years to meet the fossil fuel standards. CARB is providing time for the development of improved combustion systems for waste gas such as biogas. The proposed standards are shown below in Table 2. Our goal in this project is to achieve emissions levels that can satisfy this standard. As of April 29, 2013, there is no distributed generation technology that is certified for the 2013 non-natural gas certification.

Table 2: CARB 2013 Non-Natural Gas DG Emission Standards

Pollutant	Emission Standard (lb/MW-hr)	
	On or After January 1, 2008	On or After January 1, 2013
NO_x	0.5	0.07
CO	6.0	0.10
VOCs	1.0	0.02

1.1.3 Technology Background

The technology demonstrated in the biogas microturbine is the Low-Swirl Combustor (LSC) conceived and developed at LBNL. LSC is based on a patented technology originally developed for basic research on premixed turbulent flames supported by the US Department of Energy (DOE) (Cheng et al., *Scaling and Development*, 1305; Cheng et al. *Premixed Turbulent Flame Structures*, 29). The operating principle of LSC is fundamentally different than the conventional high-swirl method used in conventional industrial burners and gas turbine combustors. Due its origin as a research tool, the LSC concept has been investigated experimentally and engineering design guidelines and rules have been established. The basic knowledge has been applied to develop and commercialize LSC for natural gas industrial burners. Maxon Corporation, a Honeywell Company, licensed the LSC technology in 2001 and introduced the first commercial product in 2003. There are two lines of Maxon LSC burners with thermal outputs of 300 kilo British thermal units per hour (kBtu/hr) to 95 million British thermal units per hour (MMBtu/hr). These burners operate primarily on natural gas, emitting between 4 to 7 ppm NO_x at 3% O_2, meeting California's most stringent air emissions rules. To date, the two lines of products have accumulated over 1.5 million hours of safe and reliable operation.

Under DOE-Distributed Energy Resources (DER) support, an engine-ready LSC injector for Solar Turbine's SoLoNO_x™ engines (5 to 7 mega-watts [MW]) has been developed and the first round of engine tests was complete in June 2006. The LSC injector demonstrates ultra-low emissions < 5 ppm NO_x (at 15% O_2) without showing the potentials to compromise engine operation and efficiency. In 2006, DOE Office of Fossil Energy initiated a project to explore the feasibility of adapting LSC to the combustion turbines in of an Integrated Gasification Combined Cycle (IGCC) coal power plant that burns high (hydrogen) H_2 content fuels. The results from the evaluation of a reduced-scale fully-functional LSC injector at simulated gas turbine conditions showed that the basic LSC concept is amenable to fuel-flexible operation. This means that the LSC injector hardware components do not need to be adjusted when switching from high H_2 content fuel, natural gas and low-Btu fuels such as syn gases, and biogas. More significantly, the fuel-flexible LSC injector was shown to meet all performance metrics on stable operation and ultra-low emissions when operation on different fuels.

LBNL also collaborated with CMC Engineering in a California Energy Commission (CEC) Combined Heat and Power project to develop LSC for an 80 kW microturbine (CEC contract 500-03-037). The goal of the project was to demonstrate a combined heat and power (CHP) package that integrates a simple cycle, unrecuperated 80 kW microturbine (operating on natural gas) to a 30 MMBtu/hr packaged boiler. The role of the microturbine is to generate the electricity for operating the air blower of the 30 MMBtu/hr burner. The exhaust flue of the microturbine is fed to the burner intake to lower the emissions of the system. This microturbine, retrofitted with a LSC achieved ultra-low NO_x emissions level of 3 ppm at 3% O_2. Because the microturbine exhaust is fed to the burner, CO emission was not a design concern.

This project leverages prior efforts of LSC developments for gas turbines of various sizes to apply technology in a biogas microturbine to meet CARB 2103 certification. In addition to meeting the stringent emissions targets, we also strive to maintain high system efficiency, operability, and reliability.

1.1.4 Technology Description

The LSC is a dry low-NO_x (DLN) method valid only for premixed combustion. It exploits the characteristic wave property of premixed turbulent flames by enabling them to freely propagate in divergent flows that are formed only when the swirl intensities are below the critical vortex breakdown threshold. The LSC principle is fundamentally different than the high-swirl concept employed in typical DLN turbines (for example, the Solar Turbine's SoLoNO_x) where toroidal vortices with strong recirculation and intense turbulence are generated to hold and continuously ignite the flames (Johnson et al. 2867).

Figure 1: Schematics and Photographs of the Low Swirl Injector

Figure 2: The Engine-Rready LSI (Bottom) Has the Same Functionality, Size and Form Factor as Current SoLoNO$_x$ Injector (Top).

The key component of the LSC technology is a patented swirler (Figure 1) that has an outer annular swirl section with an open center-channel to allow a portion of the reactants to remain unswirled. The center-channel flow is an essential feature whose presence retards flow recirculation. Generating the appropriate flow divergence rate depends on a proper balance between the annulus swirling flow and the non-swirling center-channel flow. This can be accomplished by using a perforated screen covering the center-channel. Another parameter is the swirler recess distance, L_i (see figure 1) that controls the residence time of the interaction between the swirled and unswirled flows.

The low-swirl injector (LSI) developed for natural gas operation is made from a swirler designed for Solar's SoLoNO$_x$ engines. It has been altered to have an open center-channel. To configure for gas turbines, we applied the engineering rules developed for atmospheric low-swirl burners that are specified in terms of the swirl number 0.4 less than S less than 0.55 and the swirler recess 2 less than L_i/R_i less than 3. Figure 1 shows the benchmark LSI for natural gas. It produces a signature lifted flame that is a unique feature of the LSC method. This flame feature is quite different than the attached flames produced by conventional high-swirl combustors such as the SoLoNO$_x$ injectors.

Under prior year support, a fully functional engine-ready LSI prototype (Figure 2) has been developed for Solar's Taurus 70 (T70) engine. This LSI is a plug-in replacement for the SoLoNO$_x$ injector having the same size and form-factor (Figure 2). It incorporates a simple multi-spoke type fuel premixer and has a central pilot to assist startup and load change. The LSI has been tested in a T70 engine at Solar Turbine and shows trouble free operation at spin-up, idling, light-off, load-transition, and normal operations at half-load and full-load. The tests confirm the LSI concept for gas turbines and prove that the technology can meet all the metrics of DOE-DER's low emissions turbulent program.

The benchmark LSI developed for natural gas is the logical start for fuel-flexibility development. As in the past, the approach is to learn from laboratory experimentations and analyses then applies the knowledge to develop a sound methodology for turbine hardware design. Our experience has shown this to be a very cost effective process that does not require extensive and elaborate procedures involving computational fluid dynamics.

We begin by invoking the basic notion that the linear decay of the axial velocity within the non-swirling divergent flow is the foundation of the LSI flame stabilization principle. The decay rate and other characteristics of the divergent flows are controlled by the swirl number S that is a function of the geometric variables of the LSI. The velocity decay offers a "down-ramp" for the flame to maintain itself at the point where the local flow velocity is equal and opposite to S_T. Flashback can be prevented when the velocity at the exit is maintained higher than the turbulent flame speed, S_T,

More recent particle image velocimetry (PIV) studies show that the self-similarity feature of the LSC flowfields explains why the flame remains stationary regardless of the flow velocity U_0(Cheng et al., *Laboratory Studies of the Flowfield Characteristics*). The phenomenon is illustrated by invoking a balance equation for the mean axial velocity at the leading edge of the flame brush, x_f.

Equation 1: $$1-\frac{dU}{dx}\frac{(x_f - x_o)}{U_o}=\frac{S_T}{U_0}=\frac{S_L}{U_0}+\frac{Ku'}{U_o}$$

Table 3: Fuel Compositions for Laboratory Experiments

Fuel Composition	T_{ad} at $\phi = 1$ K	S_L at $\phi = 1$ m/s	Wobbe Index kcal/Nm^3
CH_4	2230	0.39	11542
C_2H_4	2373	0.74	14344
C_3H_8	2253	0.45	17814
H_2	2318	2.50	9712
0.5 CH_4/ 0.5 CO_2	2013	0.20	4182
0.6 CH_4/ 0.4 N_2	2133	0.31	6026

Here x_o is the virtual origin of the divergent flow and has a negative value. From previous studies, we shown that S_T correlates linearly with u' as $S_T = S_L + Ku'$ where S_L is the laminar flame speed and K is an empirical constant. Self-similar means that the normalized axial divergence rate, $a_x = dU/dx/U_o$, (for example, part of the second term on the LHS of Eq 2) is constant. On the far right hand side of Eq. 1, u'/U_o is also constant because turbulence generated by the perforated plate at the center channel is isotropic. The first term on the RHS tends to a small value at gas turbine conditions because typical S_L are in the order of 0.5 m/s compare to U_0 approaching 50 to 80 m/s. Therefore, Equation 1 shows that the flame position asymptote to a near constant for large U_0 independent of the equivalence ratio.

Equation 1 shows that the knowledge on S_T and its correlation with u' is key to the adaptation of the LSI for different gaseous fuels. However, the study of S_T is still an active research and data for the fuels relevant to biogases and other renewable gaseous fuels are unavailable. But a lack of scientific S_T data does not present a significant hurdle because the LSI can be used to measure S_T. Additionally, Equation 1 also shows that the changes in the empirical parameter K in the flame speed correlations does not have a large impact on the asymptotic flame positions. Therefore, provided that the slower and faster burning fuels show linear S_T correlation and the nearfield of the LSC flowfield remains self-similar, the LSC injector for natural gas can be adjusted to accommodate the differences in the combustion properties. There are of course other combustion parameters such as heat release ratio, combustion intensity and preferential diffusion of the fuel components that need to be considered. From our studies of methane (CH_4), ethane (C_2H_4), propane (C_3H_8), and H_2 flames with the LSB, contributions from these other factors are of second order.

1.2 Project Goal and Impact

Unless emission reductions from distributed generators such as microturbines can be achieved, the increasing restrictions on emissions from distributed generation facilities can be a disincentive for broader utilization of biogas resources in California to replace natural gas. Due to the difference in the combustion characteristics of biogas and natural gas, retrofitting existing microturbine with the fuel injectors or nozzles, like that of the burner of the microturbine combustion system, may not be sufficient to achieve the desired emissions, efficiency and performance goals.

The project goal is to develop and demonstrate a recuperated microturbine fitted with an ultra-low emission LSC combustor that is designed to meet the California Air Resources Board 2013 distributed generation emission standards for fossil fuels when operating on biogas. The new combustor was integrated to a Capstone C65 ICHP system for demonstration at the Santa Margarita Water District's Chiquita Water Reclamation Plant, in San Juan Capistrano, California (McDonell, "Chiquita Water Reclamation plant"). The anticipated benefit to the Chiquita Water Reclamation Plant (CWRP) host site is the opportunity to evaluate a new technology that meets the stringent 2013 CARB emissions standards. The project will allow the CWRP engineers to gain the operating experience with biogas-powered LSC technology.

California will benefit from increased electricity generation, reduced emissions, and demonstration of a biogas-powered recuperated microturbine that meets the CARB 2007 natural gas requirements. The development of a biogas-powered generator that meets the emission requirements will allow for increased utilization of biogas resources within the State, which will reduce demand for natural gas and increase electricity generated within California. This will have the effect of providing cost savings for both natural gas and electricity.

CEC analysis indicates that up to 100 MW of electricity could be generated from landfill sites. The report prepared for the CEC PIER Renewables Program indicates that landfill gas and biogas from wastewater treatment plants have the potential to contribute 5 gigawatts per hour (GWh) of electricity annually (almost 1.8% of the State's electricity demand). There is potential for biogas production from agricultural byproducts such as manure and food processing waste that could provide additional electricity production. Over the longer term, biomass such as crop waste and forest byproducts could be used to generate biogas through microbial conversion or gasification to provide an additional renewable energy resource. California has recently enacted A.B. 32, the Global Warming Solutions Act. This legislation will promote use of biogas and other alternative fuels in place of natural gas and other fossil fuels.

There will be benefits to air quality in California as more biogas resources are utilized cleanly. Currently some biogas production is flared off. The combustion conditions in flares are very poorly controlled, and flares produce substantial amounts of NO_x and unburned hydrocarbons. Additional benefit arises from the distributed generation aspect of the energy. Distributed production of electricity reduces the need for additional capacity of the distribution grid for transportation of electricity in California. Electricity demand in California is increasing as the population grows, and the distribution grid does not have the capacity to meet the expected demand in the future. Expanded distributed generation can reduce the need for enlarging the electric distribution grid in the State.

CHAPTER 2:
Project Approach

Our overall approach is to engineer a LSC combustor designed specifically for biogas operation and integrate it to a Capstone c65 ichp microturbine CHP system. The C65 ichp includes a C60 microturbine with a water heater exchanger mounted on its top. The microturbine generates electricity while the exhaust gas from the microturbine is used for heating water. The modified Capstone C65 was designed for the installation at the Chiquita Water Reclamation Plant (CWRP) in San Juan Capistrano, CA. In 2001 CWRP installed a 120 kW CHP system for distributed power generation using biogas generated from the waste water. This CHP system consists of four Capstone C60 60 kW microturbines. The unit developed for this project, i.e. a modified Capstone C65 ichp, replaces one of the four C60 at CWRP. Since the exhaust from the four C60 microturbines at CWRP are fed to a central water heating system for heating the anaerobic digesters, the hot water from the LSC powered C65 ichp is integrated to the hot water circuit.

The project team members are from the Combustion Technology Group at LBNL, the University of California Irvine Combustion Laboratory (UCICL), and the Chiquita Water Reclamation Plant and Capstone Corporation. The design, fabrication, and initial testing (at standard atmospheric conditions) of the LSC silo-combustor was led by LBNL. The integration of the LSC silo-combustor to the C65 and modification of the C65 liner was led by UCICL with participation from engineers from Capstone. UCICL also led the preparation and installation of the modified C65 ichp at CWRP with support from the CWRP staff members. Demonstration of the LSC C65 ichp systems was led by CWRP with support from UCICL staff.

2.1 Project Objectives

2.1.1 Technical Objectives

- Develop a microturbine-based CHP package capable of operating on biogas with ultra-low emissions that satisfies the 2013 CARB standards for waste and biogas fuels.
- Achieve a net system efficiency of greater than 65% from the biogas-powered microturbine CHP package.
- Develop a low swirl combustor for the microturbine that displays stable operation and low emissions with biogas with a range of heat contents that is suitable for many biogas sources in the state, including landfills, wastewater treatment plants, and dairies.
- Develop a microturbine with a low swirl combustor that has at least 50% turndown while maintaining ultra-low emissions that satisfy the 2013 CARB requirements, so that the system will operate on a range of fuels, from low heat content biogas to natural gas while achieving satisfactory emissions.

2.1.2 Economics/Cost Objectives

- Operate a microturbine on biogas and meet CARB emissions requirements without expensive post-combustion exhaust clean-up.
- Achieve microturbine operation on biogas with a normal maintenance cycle, and avoid frequent maintenance associated with catalytic combustors.
- Demonstrate the ability for microturbines to transition to the CARB 2013 emission standards for waste gas with small incremental cost (less than 20% of the turbine cost).

2.2 Project Tasks

Task 1: Design and Fabrication of a LSC Combustor for Biogas-Powered Recuperated C65 ichp

Task 2: Test and optimize Low Swirl Combustor and Recuperated Microturbine on simulated biogas at Lawrence Berkeley National Lab and U.C. Irvine Combustion Laboratory

Task 3: Site preparation at Chiquita Water Reclamation Plant

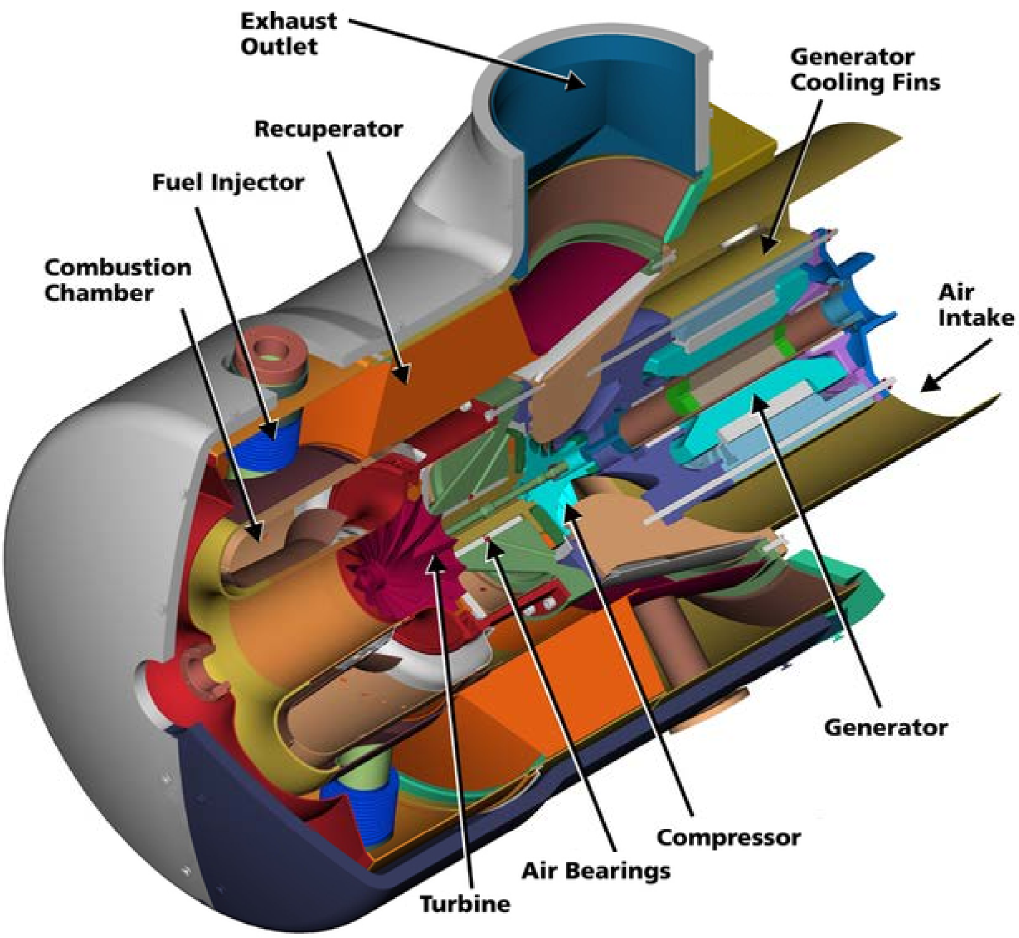
Task 4: Maintenance on the fuel treatment system for the microturbine

Task 5: Test, optimize and demonstrate microturbine performance on biogas from Chiquita facility

Chapter 3
Results

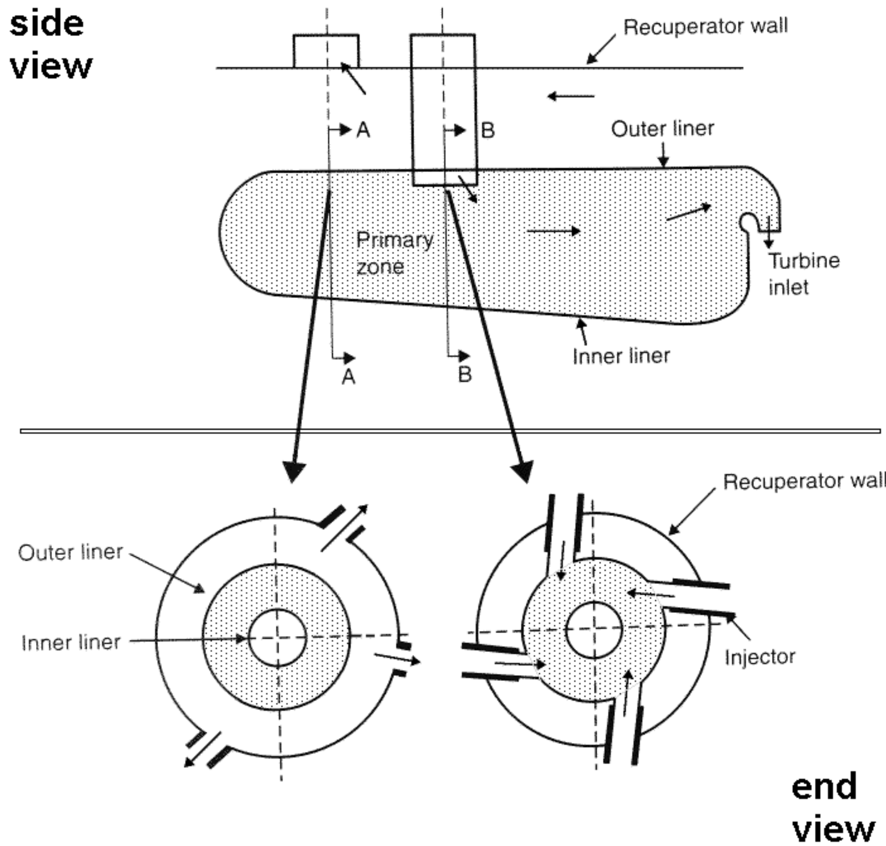
3.1 (Task 2.2) Design and Fabrication of a LSC Combustor for Biogas-Powered Recuperated C65 ICHP

Figure 3: Cutaway of the C60 Capstone Microturbine



The overall layout for adapting a low swirl combustor to the C65 microturbine was planned and designed in collaboration with the combustion engineering team at Capstone. As shown in Figure 3, the C60 (the microturbine of the C65 ichp) is compact with the fuel injectors, combustion chamber, turbine, compressor, the recuperator, and the power generator all fully integrated. Additionally, the C60 has six small fuel injectors directed into an annulus shaped combustion chamber. The multiple fuel-injector approach and the annulus combustor geometry are not well-suited for LSC adaptation.

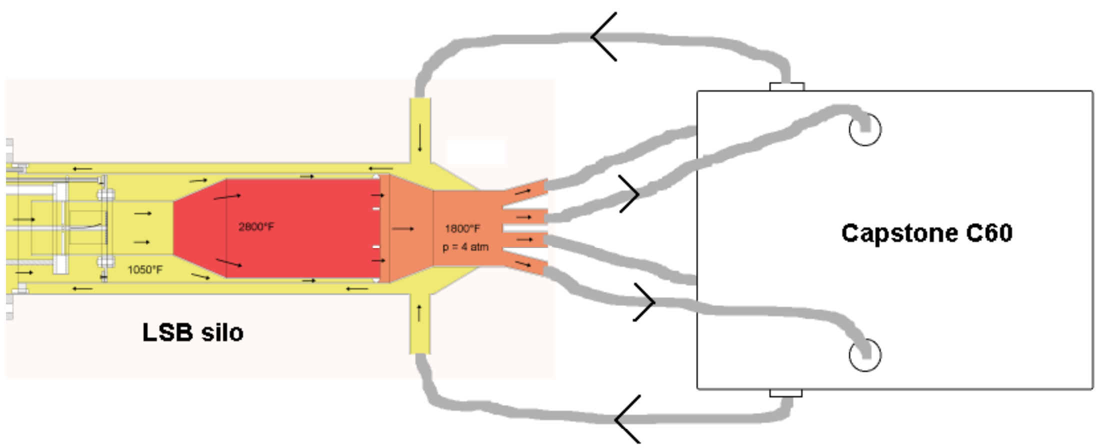
Figure 4: Schematics of the Modified Flow Path



The LSC is more suited to a single nozzle/injector implementation and its flame shape is more amenable to a cylindrical shape combustor. In adaptation to an Elliott T80 microturbine for a previous CEC funded natural gas CHP system demonstrated by CMC Engineering (CEC project 500-03-037), a silo combustor approach was developed and it has shown to have good performance characteristics in terms of emissions, efficiency and stability. To take the same approach of adapting a silo LSC combustor external to the gas turbine unity, Capstone engineers pointed out that the modification of the C65 to add an external silo would be complicated, since the recuperator is integrated into the shell and the flow into the combustion chamber is distributed through multiple fuel injectors. However, Capstone engineers also indicated that they have prior experience in incorporating an external heating system into the C60 for research studies on Brayton cycle conducted by Barber-Nichols and Sandia National Laboratory. In these modified systems, the air from the outlet of the recuperator was directed out of the turbine to an external heat source. The heated air was then fed back into the turbine's existing combustion chamber, and then to the turbine. The modified flow path configuration, (Figure 4) developed based on the Barber-Nichols and SNL configuration, was selected as the strategy to integrate a silo LSC combustor to the C65.

The engineering plan for the integration is to remove the six fuel injector tubes and replace them with suitable sleeves to re-direct the flow of air. Instead of air from the recuperator flowing into the fuel injector tubes, air flows out of the microturbine housing through the sleeves. Air flowing from the sleeves into the LSC silo combustor is mixed and reacted with the biogases. The hot exhaust from the combustion process would be split into multiple streams and fed back through some of the sleeves to the combustion chamber of the C60. In addition to the six fuel injection ports, the C60 microturbine has a seventh port for an ignitor that is also available for flows in case there is a need to accommodate for the larger volume of the exhaust gas from the LSB silo. To accommodate the change in volume, two ports will be used to take air out of the microturbine housing, and four will be used to feed the hot exhaust back in. Calculations have determined that the velocities through the sleeves will be acceptable and the pressure drop will have a significant impact on engine operation.

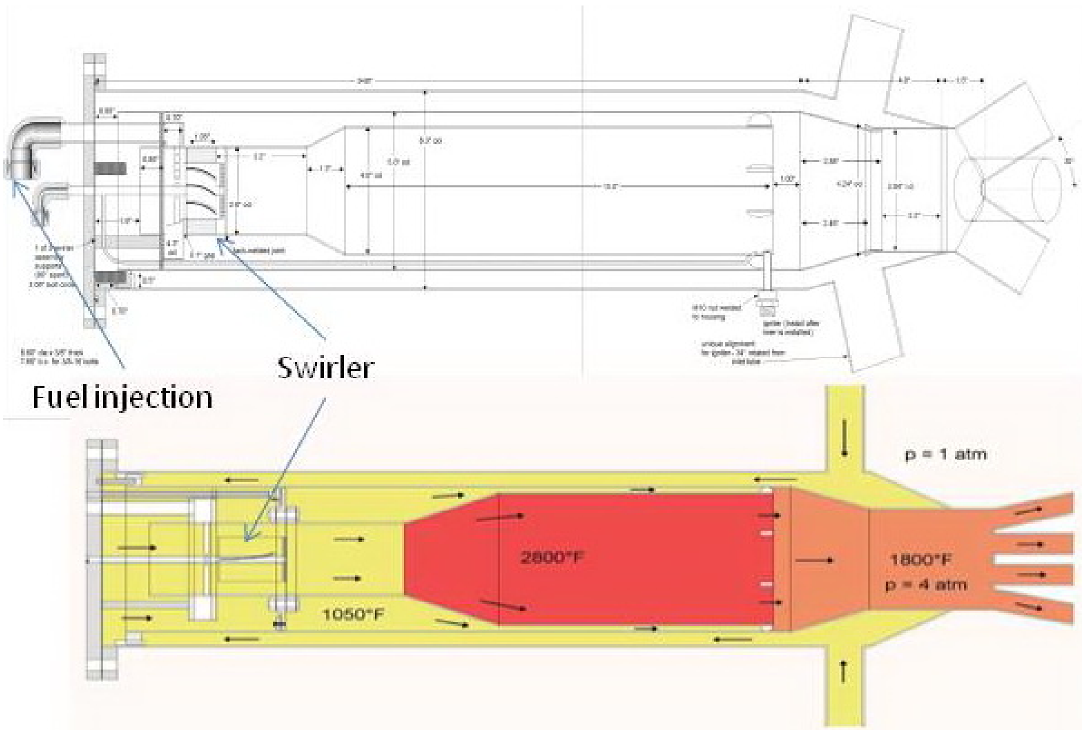
Figure 5: Schematic of the Integration of the Silo LSC Combustor With the Capstone C60 Microturbine.



The integrated system is shown schematically in Figure 5. High temperature tubing will transfer the air to the combustor silo and the exhaust back to the microturbine. Capstone engineers consider this arrangement to be the optimum for integrating the LSC combustor to the C60 engine as it involves the minimum amount of engine modification and a reasonable cost of adaptation. There is also practical benefit as the externally mounted LSC silo combustion allows good access so it can be easily monitored during the development and testing. This design will also allow the components to be separated to simplify shipping to the installation site. The main disadvantage of this design is that the external silo-combustor will not be optimum for system efficiency as it has the potential of losing heat to the atmosphere.

Design for the LSC silo combustor follows that of the one developed for Elliott T-80 with similar specifications for the components and flow paths within the silo. For integration to the C60, specifications were developed for the loads on the components, the seal on the end flange, and for the operating conditions. The material for the transfer tubes between the silo LSC combustor and the C60 was one of the original concerns because of the high temperatures of the return exhausts. Consultation with tubing manufacturers regarding this arrangement indicated that there are reasonably priced materials that will offer good durability at high temperatures.

Figure 6: Engineer Drawing of the LSC Silo Combustor (Top) and Schematics of the Flow Paths (Bottom).



Engineering drawing of the LSC silo combustor is shown in Figure 6. The basic layout is the same as the one developed for the Elliott T80 microturbine.

The three components of the LSC silo combustor is shown in Figure 7. The innermost component is the combustor consists of the swirler, the premixer, and the flame tube. Enclosing the combustor is the liner to form a narrow annular gap outside the combustor for supplying the dilution air to the combustion exhausts products. The outer housing consists of the flow tubes for receiving the compressed air from the C60 compressor and deliver the combustion exhaust back to the C60 combustor.

The overall flow paths of the LSC silo combustor is illustrated in schematics of Figure 6 (bottom). Here, the background colors correlates to the different temperatures within the silo. Pressurized air from the C60 compressor is delivered through the two tubes that are opposite to each other. Upon entering the silo, the air flows in the narrow annulus gap formed between the silo housing and the liner and turns 180 degrees at the end of the silo to enter the liner. Here the air flow is split into two streams. The bulk of the flow (primary air) enters the combustor and mixer with the fuel prior to entering the swirler. The flame is stabilized in the conical part of the flame tube and increases the temperature to about 2800°F (1538°C). At the exit of the flame tube, the combustion exhaust mixes with the remaining air flow (secondary air) from the narrow annulus between the flame tube and the liner and lowers the temperature to a level (about 1800°F [982°C]) that is acceptable for delivering back to the C60 via four tubes. This design allows for the use of perforated plates with appropriate blockages to the secondary air flow path for adjusting the ratio between the primary and secondary air flows. This is an option for optimization. The LSC silo combustor is fabricated primarily from the high temperature alloy Hastelloy X, which should provide a long lifetime in spite of the high operating temperature associated with a recuperated microturbine.

The heart of the LSC silo combustor is called a swirler, shown in Figure 7. This design follows those developed for the Elliott T80 and Solar Taurus T70 which consists of sixteen constant radius curvature thin vanes in the annulus section, and a center channel a perforated cover plate for balancing the flow split between the center non-swirling and the annulus swirling flows. The size of the center channel is 55% of the nozzle diameter. This ratio is typical of all LSC designs. At the center of the perforated plate is the pilot which is a fuel jet for startup. The main fuel is supplied by a set of fuel spokes upstream of the swirler. To accommodate biogas operation, the number and size of the fuel injection ports were enlarged for the higher fuel volume. The swirl number of the LSC swirler is also increased slightly (by increasing the blockage ratio of the center perforated plated) to account for the slower turbulent flame speed of the biogases. These changes are relative minor because of the fuel-flexible capability of the LSC concept as discussed in Section 1.1.4. In the next section, the results of laboratory tests have shown this LSC silo combustor designed for biogas can also operate on natural gas without compromising emissions and performance.

Figure 7: Top View of the LSC Swirler

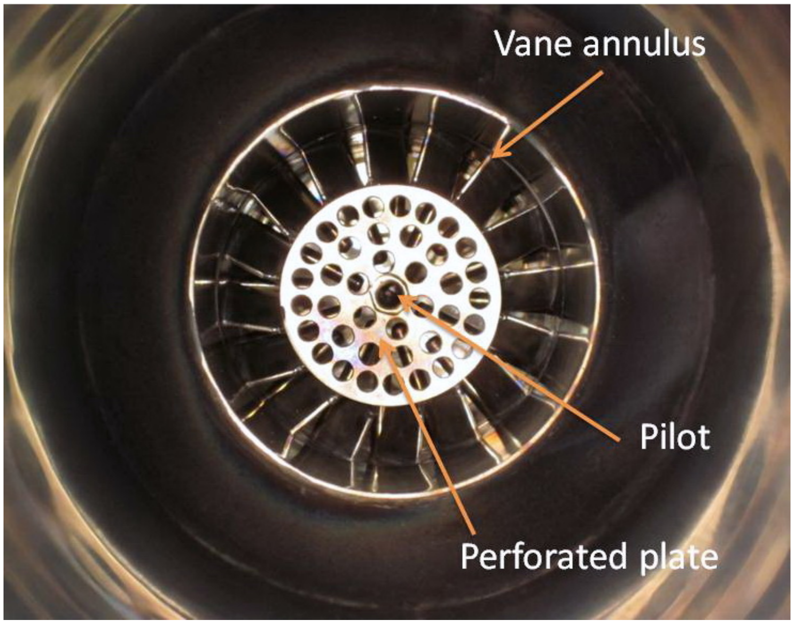
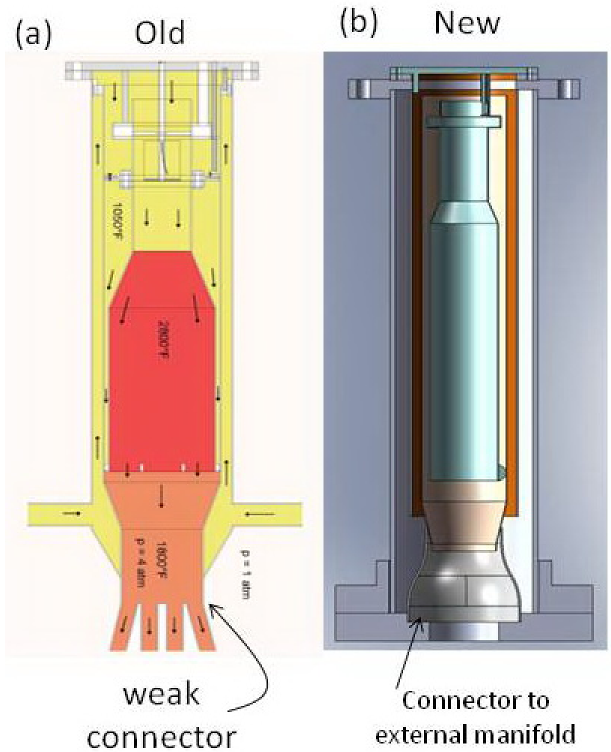


Figure 8: The Setup for Evaluation the LSC Silo Combustor at Simulated Microturbine Conditions.

The first step to characterize the LSC silo combustor involves backpressure measurements to insure that the system is compatible with the microturbine flow parameters. Since the C60 operates properly only when there is suitable backpressure in the combustor assembly, and the low swirl combustor silo has been tuned to be compatible with the Capstone flows. Additionally, tracer gas flow measurements were also conducted to assess the flow split between the primary air and secondary air flow paths. Based on the results, a suitable flow control plates for the secondary air path was designed and fabricated.

Figure 9: Schematics of the LSB Silo Combustor with (a) the Old and (b) a New Exhaust Connector.

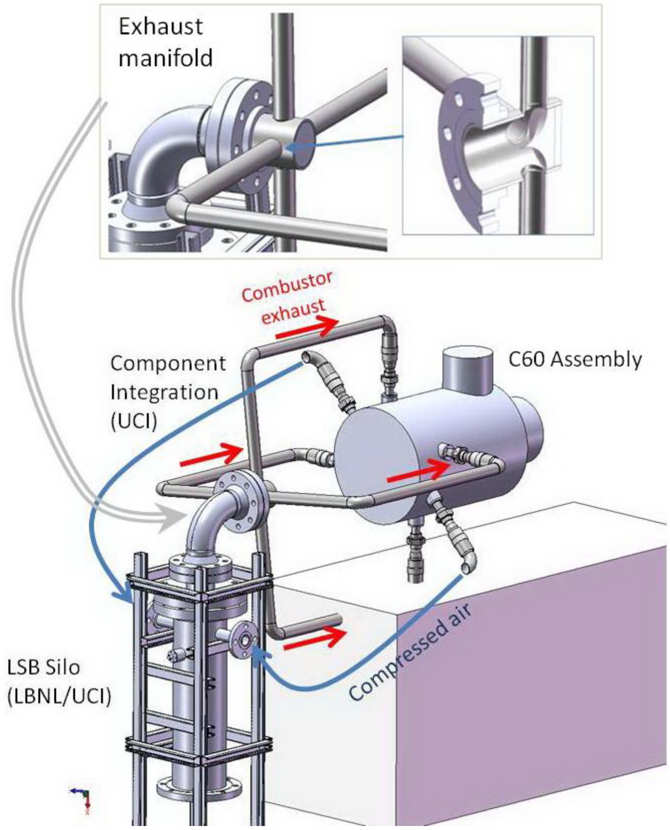


Successful completion of the LSC silo combustor tested at atmospheric conditions led to its evaluation at simulated microturbine conditions. The evaluation was conducted at UCICL in a setup showed in Figure 8. Though the results indicated that the LSB silo combustor can perform at the designed operating conditions and meet our emissions goals (see Section 3.2), it was observed that the connectors for the four exhaust gas tubes may not be sufficiently robust. The weakness of the original design (Figure 9a) with a manifold attached to the exit of the silo is that welding between the tubing may not be sufficiently rugged to withstand the vibrations during its operation. In the redesign, the silo combustor is connected to a large tube (Figure 9b) that feeds into a more rugged “cross-type” manifold (Figure 10). With these modifications finalized, the connector, manifold and tubing were also redesign for the connection scheme that is also shown in Figure 10:

3.1.1 Modification of C60 Engine and Injector Mounts (Capstone Lead)

Modification of the C60 to accept the LSB exhaust requires the expertise of the Capstone design engineers and their specialized equipment to dismount and remount the hardware components. Working closely with Capstone engineers, the UCI engineering team finalized the modifications design that includes (1) elimination of some dilution holes from the existing liner and one row of injector holes and (2) a modified injector set to inject combustion exhaust instead of reactants.

Figure 10: A Redesigned Manifold for the LSB Silo-Combustor Exhaust and Connection to the C60n Assembly.



3.2 (Task 2.3) Test and Optimize Low Swirl Combustor and Recuperated Microturbine on Simulated Biogas at LBNL and UCICL

3.2.1 Atmospheric Tests

The evaluation of the LSC silo combustor at atmospheric conditions was conducted at the Combustion Laboratory at LBNL. The first step involved non-reacting flow tests to assess air-fuel mixing and flow backpressures through the pilot and main fuel flow channels. The next step was to assess flame light-off and flame stability to identify suitable operating conditions for natural gas operation. Baseline emissions measurements were obtained for natural gas before proceeding to evaluation using simulated low Btu fuel.

Table 4 shows examples of the conditions for the atmospheric tests designed to simulate the operating conditions in a microturbine. The simulated biogases consist of CH_4 and CO_2 that are the two key components. Due to the dilution effects by CO_2, the flame speeds of syngases decrease with increasing CO_2 percentage. In microturbine operation, this decrease is offset by operating at slightly richer conditions as shown by the increase in the equivalence ratio (i.e. fuel/air ratio) when CH_4 is diluted. The richer conditions are also needed to maintain the desired exhaust exit temperature, which decreases as the content of inerts in the fuel increases.

When installed in a microturbine, the weakest fuel (i.e. the lowest fuel heat content in terms of Btu/ft^3) that the LSC silo combustor can operate on would be determined by the microturbine operating characteristics. Another consideration for operating a microturbine on biogas is the maintenance of consistent mass flow rate when the fuel content changes. As in all gas turbines, the C60 requires a fixed mass flow at 100% load. The increasing content of inert gases such as CO_2 in the fuel not only lowers the heat content of the fuel but also requires less primary air (i.e. air supplied to the LSC nozzle) for the system maintains a constant overall mass flow. This is also indicated in Table II:

Table 4: Operating Conditions for the LSC Silo Combustor at Atmospheric Condition to Achieve Constant Exhaust Temperature

Fuel	Fuel Flow		Airflow		Equivalence ratio
	CH_4	CO_2	(primary)	(secondary)	
CH_4	1	0	179	302	0.47
60%CH_4 40% CO_2	1	1.18	168	304	0.5
40%CH_4 – 60%CO_2	1	4.8	156	305	0.54

The baseline results of the LSB silo combustor for CH_4 operations are shown in Figure 11. The NO_x and CO emissions are plotted as a function of flame temperature. The results are corrected to 15% oxygen, which is the standard practice for presenting of turbine emissions data. As can be seen, NO_x emissions from the LSC silo combustor correlate well with flame temperature. This trend is consistent with the formation of thermal NO_x which is the dominant formation mechanism. The NO_x emissions are mostly single digit. At a flame temperature approaching 3000°F (1650°C), the LSC silo combustor emits just over 10 ppm NO_x corrected to 15% O_2. These NO_x emissions are consistent with those from atmospheric tests of LSC injectors developed for other gas turbines. The CO emission trend is also typical of LSC injectors with the highest at the lowest flame temperatures because the exhaust is too cool to completely burn out CO. For the laboratory tests, the CO emissions is expected to be higher than in a microtrubine setting. This is because the emissions sampling probe was located inside the LSB silo at a location before the exhaust silo exit. As CO will continue to oxidize as the exhaust flows to the microturbine inlet, so the CO emissions is expected to be lowered when integrated to the microturbine. The CH_4 test indicated that the LSC silo combustor is fuel-flexible offers a wide range of flame temperatures that can provide satisfactory emissions in an installed microturbine system.

Figure 11: Baseline NO_x (Left) and CO (Right) W\Emissions of a LSC Silo Combustor Operated on Ch_4 at Atmospheric Conditions

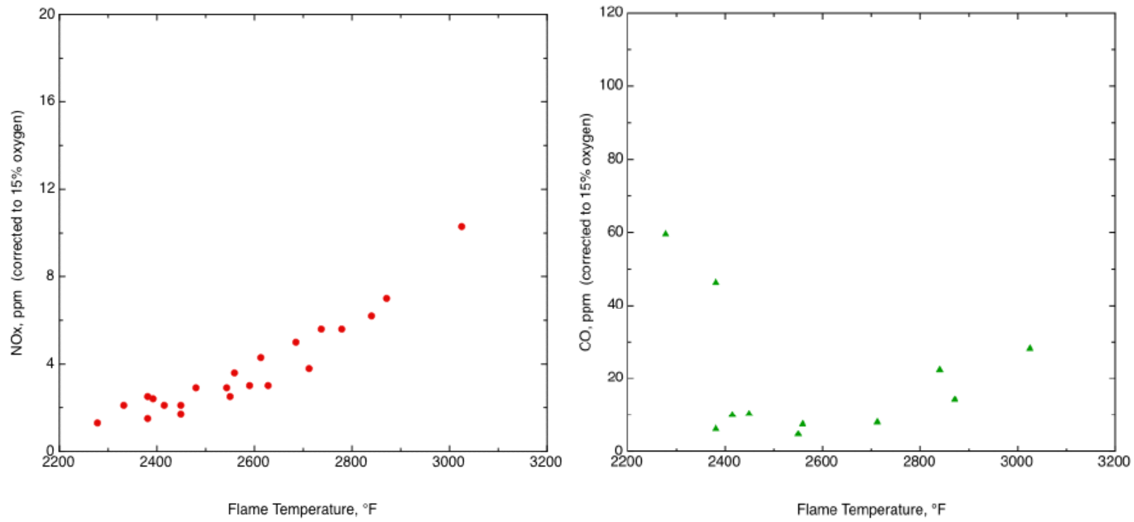
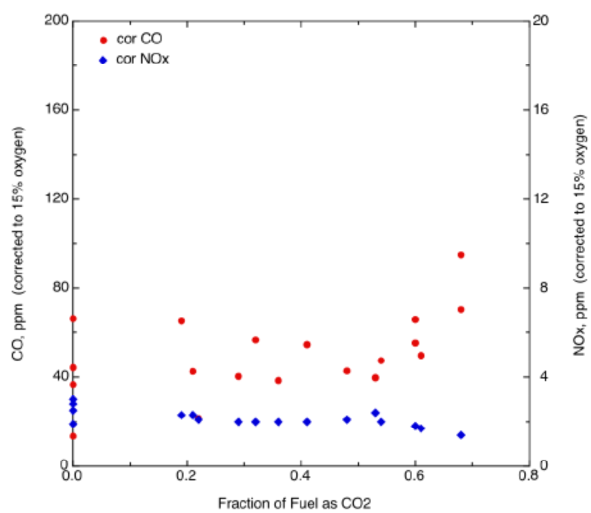


Figure 12: Effect on Emissions of Adding Carbon Dioxide as a Fuel Inert Component.



The CO_2 percentage in the CH_4 – CO_2 fuel blend was varied between 20 to 65% covering the range found in typical biogases. For all these fuels, the combustor operating conditions were selected to provide flame temperatures in the range of 2600-2700°F. This range of flame temperatures is where the emissions of NO_x and CO are low when burning pure CH_4 (see Figure 11). For this series of simulated biogas experiments, the air and methane fuel flow rates were kept constant, while CO_2 flow was increased from 0 to 65% of the total fuel volume. This way the heat release of the tests was kept constant. However, the CO_2 addition had the effect of decreasing the flame temperature as the fraction of CO_2 in the fuel blend increased. The effect of the lower flame temperatures is noticeable in the emissions at CO_2 fuel concentration above 55% where NO_x decreases to below 2 ppm at 15% O_2 and CO increases to 90 ppm at 15% O_2. To offset this effect in microturbine operation, the equivalence ratios would need to increase. For the fuels with the highest CO_2 content, despite the fact that the lower flame temperature also means the flame is weaken, none of the tests at atmospheric conditions show symptoms of flame instability.

Other operating parameters relevant to the situations in a microturbine were also studied at atmospheric conditions to assess their effect on emissions and flame stability. In a microturbine the combustor flow velocity varies significantly during lights off and when ramping up to full speed. To simulate this condition, the flow velocity in the LSC silo combustor was varied over a 3 to 1 range. The LSC silo combustor exhibited good flame stability without inciting rumbles and showed low emissions over the entire range. Additionally, the microturbine starts up at a low speed and low flow rate compared to its normal operating conditions. To insure that the combustor lights off easily, some of the fuel is fed to the central pilot shown in Figure 7. Test of the light-off procedure using the pilot showed that the LSC silo combustor lit off without difficulty with the spark igniter. After lit-off, we also operated the LSC silo combustor with up to 10% of the fuel supplied through the pilot and found that it has a minor impact on emissions. The effect of the air flow split between the primary (combustion) air and secondary air channels in the LSC silo combustor was also investigated. The flow split ratio did not significantly affect the combustor performance as long as the flame zone was maintained at acceptable operating conditions. An air flow split has been selected that will provide a suitable turbine inlet temperature for the microturbine and low emissions while running on simulated biogas.

Tests of the LSB silo with CH_4-CO_2 fuel blends (to simulate biogas with various heat contents) at atmospheric pressure indicated that the LSC silo combustor functions well on fuels with a wide range of heat content. The combustor is stable over the entire range of fuel blends tested, and low emissions could be obtained with natural gas and the simulated biogases. These so-called “stand-alone” test where the combustor is not connected with other components of the system, the silo can operate with simulated biogas with less than 200 Btu/cu ft heat content. This shows that the basic design of the LSC silo combustor has good fuel-flexible capability. However, to fully exploit the fuel-flexible capability of the LSC silo combustor in a microturbine would require the optimizing its integration to the system.

3.2.2 Laboratory Tests and Verifications at Simulated Microturbine Conditions

The LSC silo combustor for the Capstone C60 was installed in the U.C. Irvine combustion laboratory high pressure system as shown in Figure 8. The first tests were conducted at 1 atmosphere pressure to verify the functionality of the fuel supply, ignition system, flow system controls, and monitoring equipment. These were followed by light-off tests using room temperature air and ramping up fuel flow while activating the spark ignition. As discussed in Section 3.2.1, a portion of the fuel was fed to the central pilot for light-off. The purpose of these tests was to investigate the amount of pilot needed for reliable and safe light-off. Though we found that the LSC silo combustion can be lit-off with 5% of the fuel feeding the pilot, significant noise and pressure fluctuations were observed after the flame was lit. When the pilot was increased to 10% the flame was much quieter and stable. We also found that when the air flow increased to the conditions equivalent to those for microturbine operation, the pilot fuel can be shut off and the flame remained stable with little fluctuation in pressure. Lean blowout tests were also conducted at these conditions, and the results were similar to observed in testing at atmospheric conditions. Upon the completion of the atmospheric tests, the evaluation continued with air preheated to 680 K (760°F) at 1 atmosphere pressure. As expected, the preheating provided a significant improvement in lean blowout conditionsAt UCICL, the evaluation of the LSC silo combustor at simulated gas turbine conditions of preheated air at 4 atm (atmosphere) pressure commenced upon the completion of the atmospheric tests. The light-off procedure developed from the atmospheric pressure tests was found to work well at elevated temperature and pressure and no issue was found with light-off. As in the atmospheric tests at LBNL, simulated biogas (in this case natural gas instead of CH_4 and CO_2) were used. These experiments showed that the LSC silo combustor operated with fuel blends of up to 60% CO_2 without requiring optimization of the flow splits or other operating conditions. This result is encouraging as it implies that the control system for the C65 ichp does not need to be modified for the LSC silo combustor.

Figure 13: NO Emissions of LSC Silo Combustor at Simulated C60 Conditions

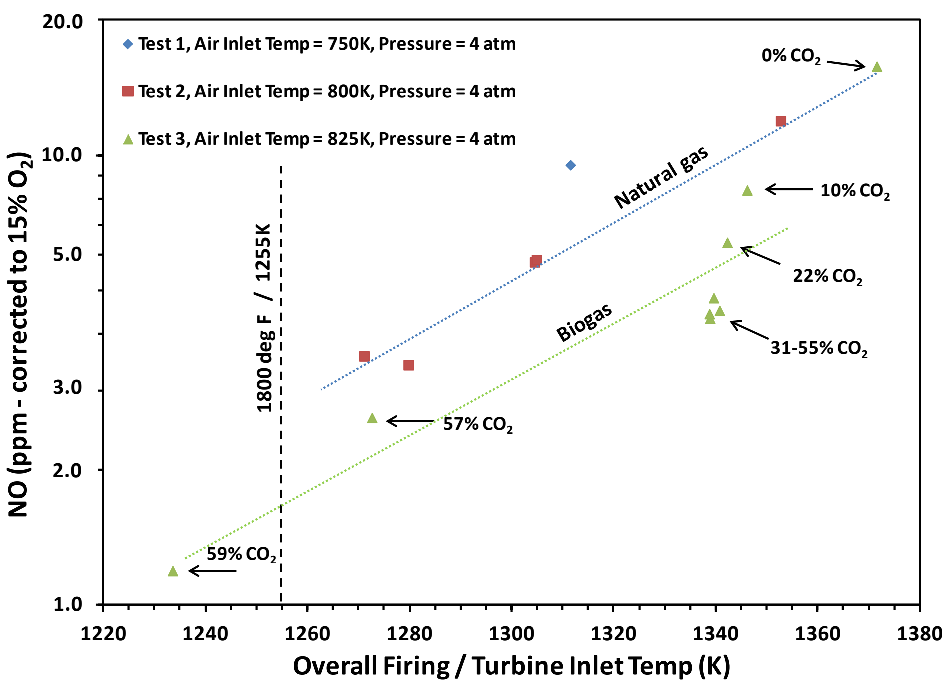
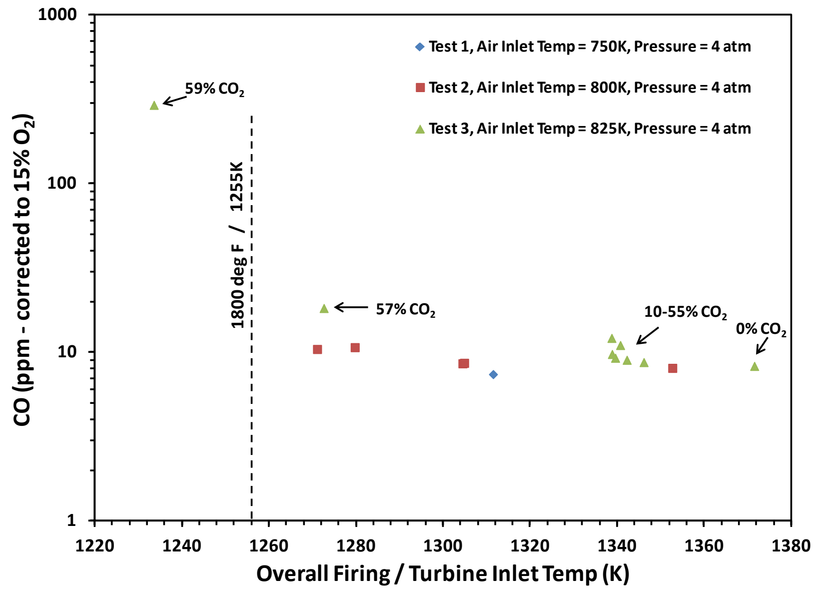


Figure 14: CO Emissions of LSC Silo Combustor at Simulated C60 Conditions



The NO_x and CO emissions from natural gas and natural gas CO_2 fuel blends are shown respectively in Figures 13 and 14. As expected, NO_x emissions increase with flame temperature and most are below 10 ppm at 15% O_2. The overall NO_x emissions of the LSC silo combustor are very encouraging and show that the technology is capable of meeting the emissions NO_x targets of 3 ppm (calculated based on CARB 2013 emissions target). However, CO emission shows a constant level of 10 ppm at 15% O_2 and significant jump to above 100 ppm at 15% O_2 for flame temperature below 1800°F (982°C). These levels are higher than the 4.5 ppm at 15% O_2 CARB 2013 standard. This implies that an oxidation catalyst may be required to meet CO emissions target.

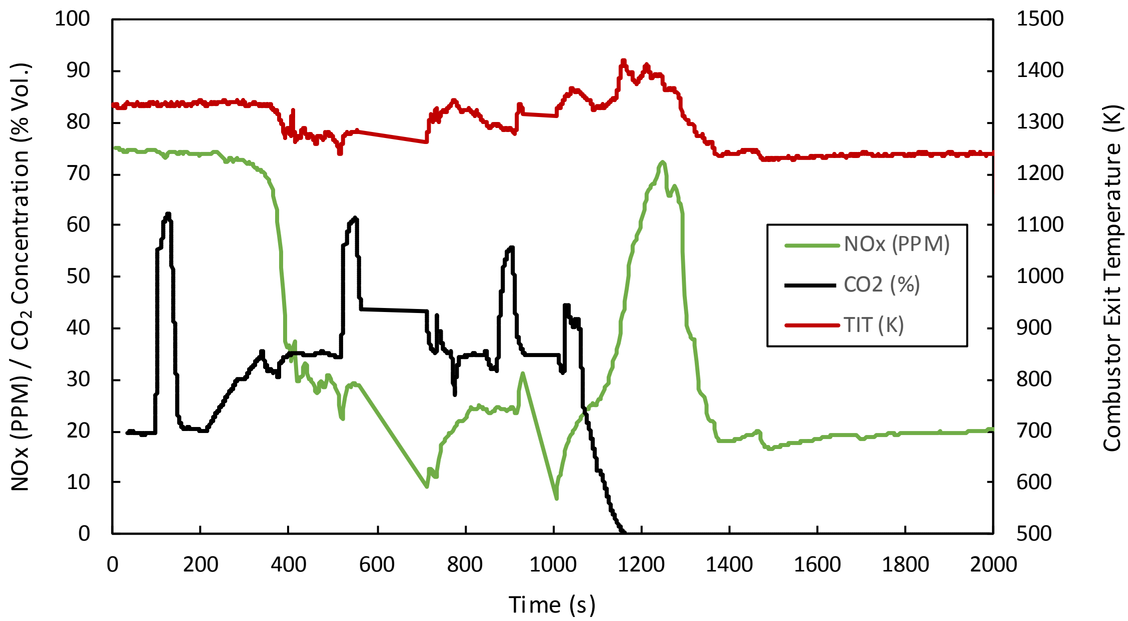
As shown in Figure 15, a capstone C60 microturbine has been modified to accommodate the LSB combustor at the UCICL. The installation proceeded smoothly, with relatively few modifications required to the actual microturbine.

Figure 15: A LSB Combustor Fitted to a Capstone C60 Microturbine at the UCICL.

It has been demonstrated that the LSB combustor can be ignited, however due to the constraints of the Capstone's internal logic, the engine will not fully operate. Typically a C60 will monitor the gas temperature at the exit of the turbine. During startup, if the turbine exit temperature does not exceed 900°F (491°C) within a few seconds after supplying fuel to injectors, it determines that the flame in the combustor has been extinguished. At this point the engine will enter its cool down routine. Due to the fact that the LSB combustor is external to the engine, there is a significant amount of piping between the combustor and the turbine. Despite being of double-wall construction, the thermal inertia of the piping absorbs a significant amount of heat immediately after ignition of the LSB combustor. Due to the internal logic of the microturbine, the combustor is not permitted to run long enough to overcome the thermal inertia of the piping and achieve turbine exit temperatures greater than 900°F. Based on these findings the C60's startup procedure was modified to bypass the default startup procedure. The C60's software was modified to simply maintain a fixed engine speed. The fuel flow to the combustor, and thus firing temperature, was controlled by an external fuel control circuit. This approach allowed for the engine to be brought up to temperature slowly, and for the firing temperature to be fixed at the desired value.

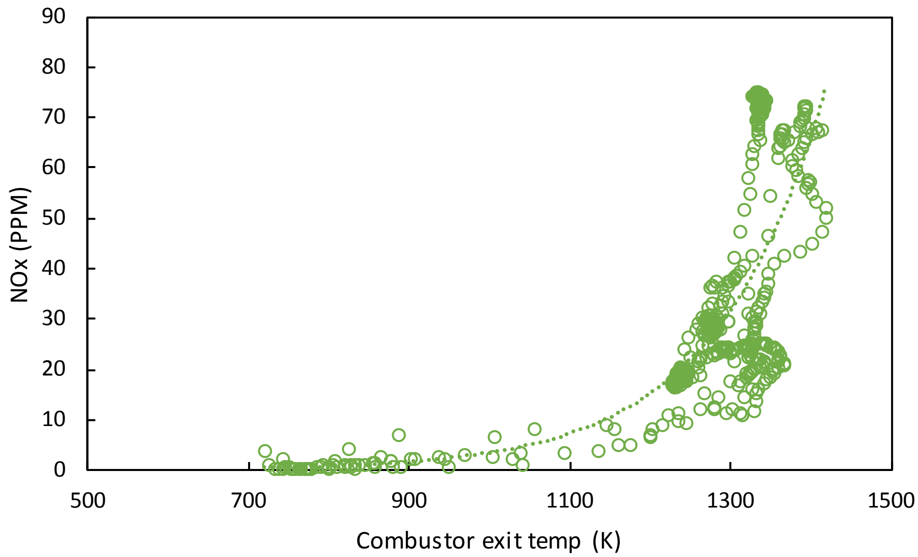
Unfortunately, due to the excessive pressure drop associated with the lengthy plumbing of the external combustor, the engine is not capable of making net power. Nevertheless, combustion tests were performed with this engine on simulated biogas. Figure 16 shows a plot of combustor exit temperature, NO_x emissions, and percent CO_2 in the fuel over the course of one test.

Figure 16: NO_x Emissions, Combustor Exit Temperature, and Fuel CO2 Concentration During Test of the LSB equipped C60



As can be seen in Figure 16, firing temperature was held between 1250 K and 1400 K. Fuel was initially comprised of 20% CO_2 and 80% natural gas, increasing to higher concentrations of CO_2, and then finally decreasing to 0% CO_2 at the end. Generally speaking, the emissions of NO_x are highly tied to the firing temperature, with higher temperatures leading to higher NO_x emissions. Fig 17 shows the general trend observed of NO_x emissions with respect to firing temperature.

Figure 17: NO_x Emissions as a Function of Combustor Exit Temperature



As shown in Figure 17, NO_x emissions tend to increase exponentially with firing temperature. Due to fluctuations in fuel CO_2 concentration, it was generally necessary to operate the combustor at a higher firing temperature than the design point (1250°K [2060°F]) to avoid blow off due to a momentary increase in the CO_2 concentration. Consequently, the emissions data at 1250°K [2060°F] are somewhat limited. When operating at the designed firing temperature of 1250K NO_x emissions were on the order of 20 PPM. Outside of its effect on firing temperature, and thus flame stability under very fuel-lean conditions, the addition of CO_2 to the fuel had no significant effect on the operation or emissions of the combustor.

3.3 (Task 2.4) Site Preparation at CWRP_Facility

UCI has been in regular communication with the points-of-contact, Don Bunts and Tracy Wallace, at the Chiquita Water Reclamation Plant to ensure an efficient transfer of the engine to the field. The preparation work is complete. The modifications include the gas lines, electrical connections and hot water connections. The site was made ready to receive and make operational the system upon completion of shake down testing at UC Irvine in Task 2.3.

Figure 18: RSM Site and Location for MTG

3.4 (Task 2.5) Maintenance on the Fuel Treatment System for the Microturbine

In preparation for the field demonstration, personnel of the Chiquita Water Reclamation Plant verified that the key components of the fuel treatment system are in good order. The completed tasks include replacing the activated carbon for siloxane removal and inspecting and verifying the integrities of the sulfur removal, refrigerated dryer (for water removal) and the gas compression systems.

3.5 (Task 2.6) Test, Optimize and Demonstrate Microturbine Performance on Biogas from CWRP

While the present work has demonstrated that it should be possible to power a microturbine with an LSC, the current setup has too high of a pressure drop across the LSC to make net power. Therefore, additional work is needed to reduce these pressure losses before the system can be deployed. To this end, Task 2.6 will not be completed.

Chapter 4: Summary and Recommendations

4.1 Summary

This project involved the development of a silo low swirl combustor for operating with biogas and its integration into a recuperated Capstone C60 Microturbine. The laboratory results showed that the low swirl combustor, when operating by itself in a well-controlled laboratory setting, achieved our operational and emissions goals. The integration of the low-swirl combustor to a Capstone C60 Microturbine required considerable modification to the engine and the addition of a piping and manifold system that substantial. This was due in part to the nature of the specific engine utilized. The integrated system required such large system pressure losses that the overall system performance was not as desired.

Ultimately, the lack of desired overall system performance precluded testing at the field site, although the site was made ready to receive the engine.

4.2 Recommendations

While this project has demonstrated the feasibility of using biogas to power a microturbine with an LSC, the current connecting system created additional pressure drop between the compressor and turbine sections that is unacceptably high for the C60 to generate net electricity power. Therefore, additional work is needed to reduce these pressure losses before the system can be deployed.

While the emissions data from the laboratory tests as well as the engine tests are promising, the system's ability to meet CARB emissions targets has yet to be verified. This is because the fluctuations in the CO2 levels in the fuel during engine tests at UCI precluded the LSC to operate at our targeted firing temperature. Such fuel fluctuation is not expected to occur at the Chiquita Water Reclamation Plant because the fuel composition would be considerably less variable. We anticipate that the LSC powered C60 Microturbine will be able to operate the designed combustor exit temperature and the NO_x emissions could be reduced. Never the less, lab testing has shown that at the reduced firing temperatures, emissions of CO may be a concern. Under these conditions it is likely that an oxidation catalyst would be necessary.

The main technical challenge encountered during the course of this project was associated with connecting the LSC combustor to the Capstone C60 Microturbine. As seen in Figure 15, the connecting pipes are about 3 ft (0.914 m) long. If the LSC could be mounted on top of the C60, the shorter pip length could reduce the pressure drops by substantial amounts.

REFERENCES

Cheng, R.K., D. Littlejohn, W.A. Nazeer, and K.O. Smith. Laboratory Studies of the FLowfield Characteristics of Low-siwrl Injectors for Adaptation to Fuel-Flexible Turbines. in ASME Turbo Expo 2006: Power for Land Sea and Air. 2006. Barcelona, Spain: ASM

Cheng, R.K., D.T. Yegian, M.M. Miyasato, G.S. Samuelsen, R. Pellizzari, P. Loftus, and C. Benson, Scaling and Development of Low-Swirl Burners for Low-Emission Furnaces and Boilers. Proc. Comb. Inst., 2000. **28**: p. 1305-1313.

Cheng, R.K., I.G. Shepherd, B. Bedat, and L. Talbot, Premixed turbulent flame structures in moderate and intense isotropic turbulence. Combustion Science and Technology, 2002. **174**(1): p. 29-59.

“Cogeneration and On-site Power Production”, Nov-Dec. 2013 - Biogas-fuelled Microturbines

Johnson, M.R., D. Littlejohn, W.A. Nazeer, K.O. Smith, and R.K. Cheng, A Comparison of the Flowfields and Emissions of High-swirl Injectors and Low-swirl Injectors for Lean Premixed Gas Turbines. Proc. Comb. Inst, 2005. **30**: p. 2867 – 2874

McDonell, Vincent G. "Chiquita Water Reclamation Plant." Membrane Technology 2002.10 (2002): 2-3. Building Microgrid. University of California, Irvine. Web. <https://building-microgrid.lbl.gov/sites/all/files/dercam_casestudy_santamargarita_v1_2%5b1%5d.pdf>.

National Renewable Energy Laboratory, (2013) “Energy Analysis – Biogas Potential in the United States”, NREL/FS-6A20-60178, Golden, CO

Report #CEC-500-2005-066-D "Biomass Resource Assessment in California

GLOSSARY

Term	Definition
Btu/cu ft	British thermal units per cubic feet
C_2H_4	Ethane
C_3H_8	Propane
CARB	California Air Resources Board
CEC	California Energy Commission
CH_4	Methane
CO	Carbon monoxide
CWRP	Chiquita Water Reclamation Plant
DER	Distributed Energy Resources
DLN	Dry low-NO_x
DOE	Department of Energy
GWh	Giga-watts per hour
H_2	Dihydrogen
kBtu/hr	Kilo British thermal units per hour
kW	Kilowatt
lb/MWhr	Pounds per mega-watt hour
LBNL	Lawrence Berkeley National Laboratory
LSC	Low-swirl combustor
LSI	Low-swirl integrator
MMBtu/hr	Million British thermal units per hour
MW	Mega-watts
NO_x	Nitrogen Oxide
O_2	Oxygen
PIER Program	Public Interest Energy Research
ppm	Parts-per million

RD&D	Research, development, and demonstration
SCR	Selective catalytic reduction
UCICL	University of California Irvine Combustion Laboratory
VOC	Volatile organic compounds